SFC GCRF Pump Priming 2018/19

Initial studies towards an innovative Floating Wind-Hydrokinetic Power Station (FWHPS) for Upper Egypt Villages

Project Report

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1. PROJECT OVERVIEW

1.1. Introduction

In the world where environmental degradation has reached hazardous levels, the transition to sustainable energy methods has become a priority for all. In this framework, renewable energy systems can play a vital role in replacing traditional fossil fuels for large scale energy generation, but this is still difficult to implement when supplying isolated micro-communities (Neves, Silva, & Connors, 2014). Many developing countries that are sparsely populated face serious problems in supplying safe and reliable electricity to communities which are situated in remote and hardly accessible areas, such as river sites, due to grid weakness which causes frequent electricity interruptions when local demand exceeds supply. The use of small scale renewable energy systems which could provide the local society with clean, safe and reliable energy could be a solution that would alleviate this problem in a sustainable manner. This is a very promising idea as there are several similar projects developed in different small islands and remote villages around the world.

1.2. Hybrid system

There are many small renewable energy sources that could be used for this purpose. In this work, the possibility of combining a small wind turbine and water current turbines in a compact structure, forming a hybrid system, will be considered and its feasibility and applicability in river sites will be examined. To design such a system, a brief review of the available market technologies in the areas of small wind turbines and river current turbines needs to be made, whereas the way of incorporating them into the same scheme should be investigated.

1.2.1.Small scale wind turbines

Small wind turbines are those which have a rated power output up to 100 kWs. Their applications may vary according to their power capacity; they can be used for batteries charging, for residential heavy seasonal loads or for supplying remote communities and commercial or institutional buildings (James & Bahaj, 2017). They are classified mainly based on their axis of rotation (vertical or horizontal axis). Some typical commercial examples are the following:

- Horizontal axis
- Darrieus type
- Savonius type

Figure 1 Group of HAWTs in a wind farm in UK (Sedaghat & Mirhosseini, 2012)

Figure 2 Darrieus type VAWT (Aggeliki, 2018)

Figure 3 Savonius type VAWT (Tummala, Velamati, Sinha, Indraja, & Krishna, 2016)

1.2.2. River current turbines

The natural power of a running river or a stream offers an opportunity for electricity production and different concepts regarding the way that this can be exploited have been developed recently, primarily for small-scale applications. There are diverse hydro-kinetic technologies which could serve this idea, most of them having a nominal power output of a few kWs (Sornes, 2010). The available turbine systems are categorised in axial flow and cross-flow turbines, the configuration of which is presented in the following figures:

a) Axial flow turbines

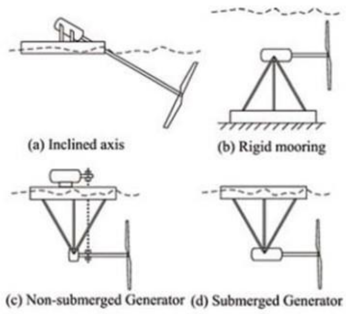


Figure 4 Axial flow (horizontal) turbines (Sornes, 2010)

b) Cross flow turbines

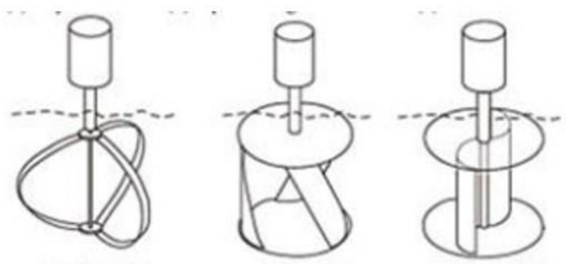


Figure 5 Different kinds of vertical axis turbines (Sornes, 2010)

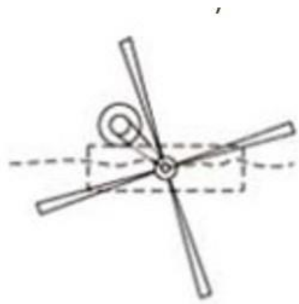


Figure 6 In-plane axis turbine (Sornes, 2010)

1.2.3. Floating platform

Although the floating platform concept is used mostly in transitional or deep waters for large-scale projects, this project scope was to investigate the possibility of using it in a shallow river to accommodate a hybrid system of wind and water current turbines for reasons that will be explained in the concept section.

The dominant classifications of floating wind structures are: the spar-buoy, the Tension-Leg platform, and the Semi-submersible platform (of various shapes). The difference among them lies on the way they achieve stability; either by using ballast like the former ones, either by having the mooring lines as their stabilised factor as the TLPs or by using the equilibrium between their weight and the buoyancy force like the latter ones.

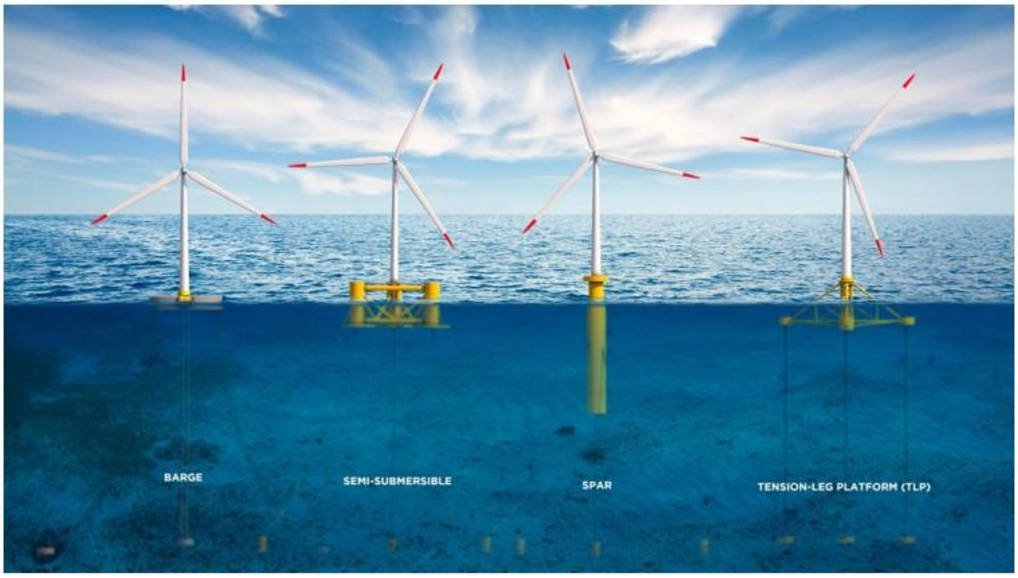


Figure 7 Barge,Semi-submersible, Spar-buoy, Tension-leg platform (Jonkman & Matha, 2010)

1.3. Project aim

The main aim of this project is to investigate the concept of a floating hybrid system which will combine wind and hydropower generation for river applications, from technical feasibility, economic viability and environmental perspectives. The platform will offer a mobile, low emission and economically viable means of power generation for the poor population in UG villages. The ultimate aim is to establish partnerships for future GCRF calls.

1.4. Project objectives

The project objectives are listed below:

1. Select an appropriate exact location within the River Nile based on its wind and current data to extract the maximum energy possible from the location of interest
2. Perform initial engineering calculations to design a floating power station and mooring lines
3. Explore the potential environmental impacts of the proposed floating station
4. Carry out a financial analysis to ensure its cost-effectiveness
5. Disseminate the project results in Egypt

1.5. Challenges

- Given that river waters are usually shallow, the geometry of the floating system should be carefully designed so that its stability can be ensured.
- The relatively low stream velocity of rivers poses another difficulty in terms of the power output to be achieved from the current turbines to render the system economically viable.
- Rivers in most cases host a significant and diverse number of fauna and flora both in the water and their banks, so the system should not cause any kind of environmental disruption.
- Other factors, such as the local legislative framework and different human activities, ought to be taken into account.

2. DESIGN

2.1. Concept

2.1.1.Concept Explanation

The concept of this project is to integrate wind and current energy resources in a floating structure, capable to be used for river applications. This novel idea is already being studied in the literature (Li, Gao, Yuan, Day, & Hu, 2018). Recent studies focused on the combination various offshore renewable energy devices to produce effective synergy in either floating or fixed structures mainly for large scale applications (Lande-Sudall, Stallard, & Stansby, 2018; Singh, Chen, & Choi, 2016). However, the scope of this project was to focus on a small-scale application in order to cope with the technical limitations, as well as the technological constraints, that could refrain the system from being expanded in large scale implementation.

Why floating?

A floating structure was chosen for this case because, contrary to a fixed construction, a floating structure offers a good solution to accommodate multiple current turbines. At the same time, theoretically, it does not present the instability disadvantage, since the waves in a river are small in height and long in the period and thus, they do not induce significant motions to the platform. Additionally, a fixed structure would create problems in fish movements and migration routes and that, in tandem with the fact that in many rivers the existence of a stationary model is legally prohibited, was a complementary reason in favour of this decision.

Advantages

- Green energy production by combining two resources; wind and water.
- Shared operation and maintenance costs.
- Independent source of electricity for remote communities.
- Potential expansion by building arrays for enhanced power generation.
- If supported by storage systems, it could operate as a dispatchable and reliable energy source that could compensate for possible grid interruptions or faults.

Disadvantages

- Not adequate power (from one system) to meet the growing needs of demand.
- High dependence on the stochastic nature of the wind that leads to unreliable and intermittent generation.
- Difficulties in the maintenance of the river current turbines.

2.1.2.Design

The final design which was developed in this project comprises 1 wind turbine and 4 river current turbines mounted on top of and beneath a barge floating platform respectively, which in turn is tethered to the riverbed with mooring lines. Below an illustration of the complete design made in Orcaflex is presented:

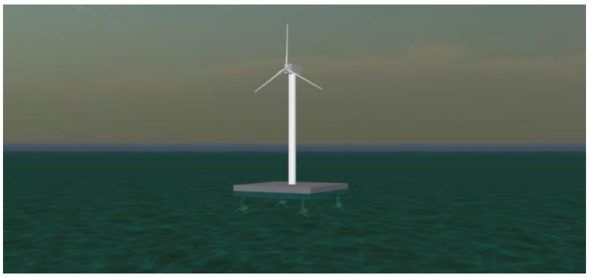


Figure 8 Complete design of HAPI in Orcaflex

2.2. Location

2.2.1. Why HAPI?

The Nile was not only the selected case study but also the inspiration for our project's name. According to Egyptian mythology, Hapi was the God of river Nile (Hughes, 1992).

The Nile is the longest river in the world and is generally characterized by its tendency to meander; this has led to changes in the value of velocity, water levels, discharge, and bed material varying from one reach to the other (Fielding et al., 2018). It was decided to focus on an area which covers a distance of 185.24 km upstream El-Roda gauge. In order to narrow down the study area, the part of the Nile that passes through city El Balyana was selected in this project.

Figure 9 River Nile, Egypt, Location of Hapi project

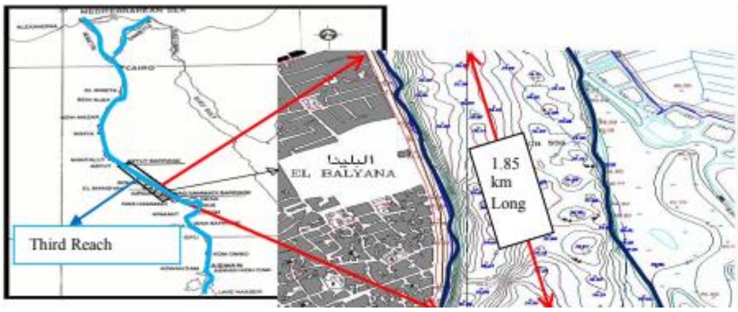


Figure 10 El Balyana, the location of Hapi project (N. Eshra, 2014)

2.2.2. Morphological factors

For the purpose of this project, various river sites that fulfil some basic factors that will be presented below were considered. The first factor considered was the morphologic characteristics of the river site. It was therefore decided to set the following reference values that would facilitate this project’s aims:

- Water Depth > 8 m
- River Width > 150 m

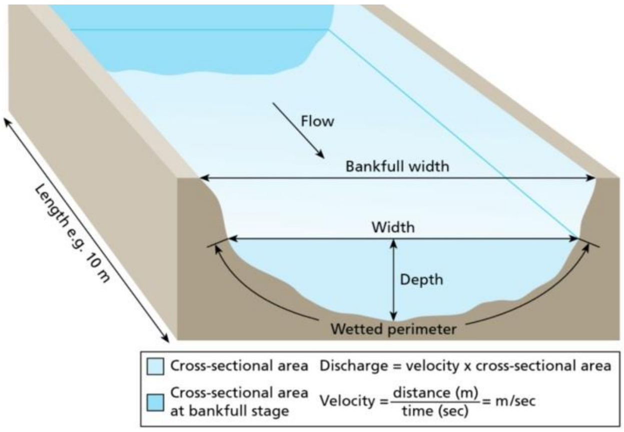


Figure 11 Hydro-graphical characteristics of a river

According to this project’s concept, the current turbines will be suspended underneath the platform base. The blades' diameters for the current turbines were selected to be 5 m. For this reason, if the height of the wet part of the platform and a safe distance of 2 m from the riverbed is added, it is found out that the river depth must be higher than 8 m. Considering the fact that the deepest points of the river are located in the central channel, the selected river must be wide enough to accommodate our platform.

The depth of river Nile changes presents high variability and it is very difficult to find accurate values for a specific part of it. Deposition and erosion take place every year that affect the river's morphology as it can be seen in Figure 12. It is clear that the deposition occurred in the East channel at the navigation path as the result of bank erosion that happened at the eastern side (Kamal & Sadek, 2017).

According to (N. M. Eshra, Abdelnaby, M. E, 2014), it is safe to consider an average of 10 meters as the river depth in a distance of 100 meters from the side banks. Moreover, a distance of 450 meters can be considered as the average width in the selected location. As can be seen, both values are within the limits of our reference values.

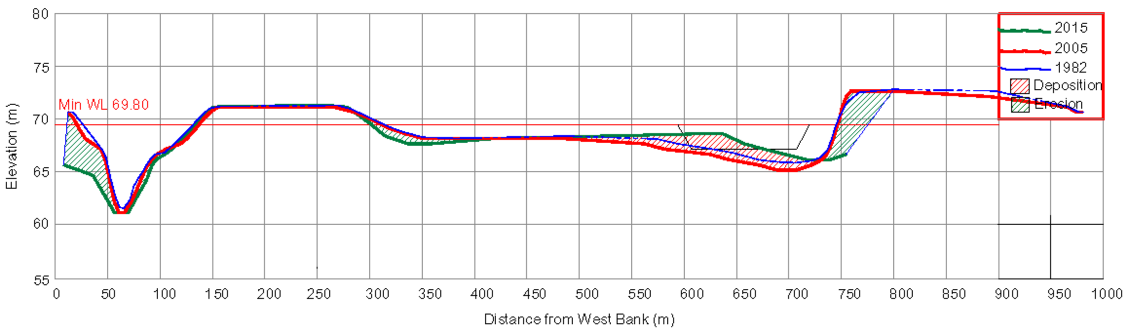


Figure 12 Navigation bottleneck cross section near our selected location (Kamal & Sadek, 2017)

2.2.3.Navigation Channel

Using the rivers for navigation has always been a good opportunity for fuel saving and for improving road safety. Especially in the Nile, cargo transportation plays a significant role in the decrease of the stress on the road network of Egypt. The Egypt Government has decided to work on the navigation development but to do so, it was necessary to modify a navigation channel design within the river course and maintain a navigational depth according to international design, while taking into consideration the stability of the Nile River (Kamal & Sadek, 2017)

Figure 13 Navigation channel near El Balyana (Kamal & Sadek, 2017)

As can be seen in Figure 13, the navigation channel does not always coincide with the central channel of the river. According to the data provided by the Nile Research Institute (NRI), every construction in the river must have a safety distance of 150 meters from the navigation channel. In our case, the width of the river ensures that the legislation, as well as the local fish-farming activities, will not be violated in any case.

2.2.4.Adequate conditions

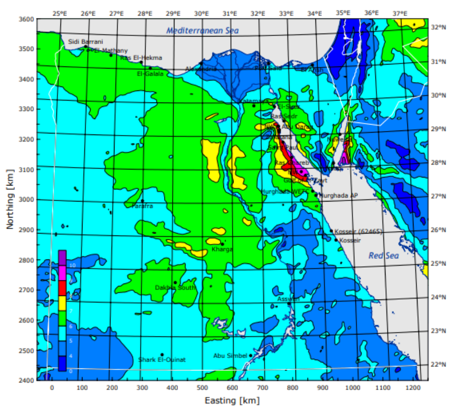


Figure 14 Wind atlas for Egypt (Mortensen, Said, & Badger, 2006)

Generally, several issues are of concern with regards to the power production performance on river applications. It should be ensured that the existing conditions in the selected area are favourable to our project. Stating with the wind profile, it has been already proposed in (Ahmed, 2011) that the specific area has adequate mean wind speed. A milestone regarding the wind data in Egypt is the 'Wind Atlas for Egypt' which was published recently by the New and Renewable Energy Authority (NREA) and the Egyptian Meteorological Authority (EMA) in Cairo, in cooperation with Risø National Laboratory (Mortensen et al., 2006).

The 'Wind atlas' provides us with analytical wind data, at a specific anemometer height, in every region across the Nile (Figure 14). As it can be seen in the Energy output, the average wind speed in our location is satisfying.

As far as the river water velocity is concerned, apart from the water discharge rate, it has been difficult to obtain analytical data. While the maximum and minimum expected water velocity values are known, there exists no solid data regarding its variability throughout the year in the open literature.

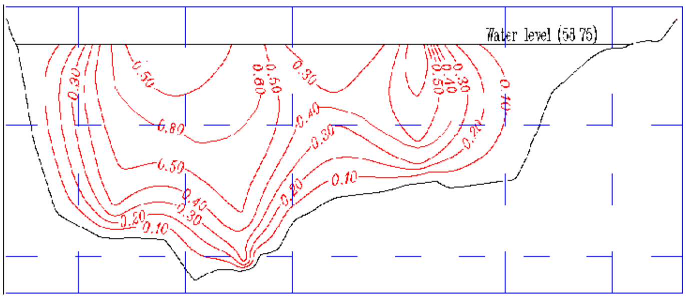


Figure 15 Bathometric data in our location (N. Eshra, 2014)

However, it is proposed to consider an average speed of 0.8 m/s which is suitable for our turbines' capacity. Moreover, the bathometric plot in Figure 15 gives a better understanding of riverbed's geometry as well as the different water stream velocities.

2.2.5. Conclusions

The chosen location has an adequate morphology which ensures that our platform will be accommodated safely. The navigation channel has been taken into consideration and has been carefully checked that legislation will not be violated. Our location offers good conditions in terms of wind speed and water stream velocity and the desired output will be achieved. However, it needs to be mentioned that there have been some locations across the Nile with better wind conditions but with smaller stream velocity. Generally, it is not easy to find a location where both resources are high.

Once the location was chosen, one big step of the project has been fulfilled. With all the data collected, the next step was to calculate analytically the estimated power output and carefully decide on our platform's geometry.

2.3. Power Output

2.3.1. Selection of wind turbine

The selection of the wind turbine was mainly based on the wind resource analysis of the site. Another decisive factor was its total height and weight, which were carefully considered so that the stability of the system would not be endangered.

The turbine is of a horizontal axis (HA) type, upwind style and has a nominal power output of 100 kW. It is developed by C&F Green Energy (Cfgreenenergy, 2018) and it is shown in Figure 16.

Figure 16 CF 100kW (Cfgreenenergy, 2018)

Table 1 Characteristic wind speeds

Characteristic speeds	
Cut-in wind speed	**3 m/s**
Rated wind speed	**9 m/s**
Cut-out wind speed	**25 m/s**

2.3.2. Wind resource analysis and energy generation

Figure 17 Wind atlas for Egypt

The first step to calculate the energy output of the wind turbine comes with the analysis of the wind data from the chosen site. Data about the wind distribution direction was obtained from (Windfinder, 2018) and based on that a suitable positioning of the wind turbine was found so that it is turned to the main direction of the wind. Also, the frequencies of occurrence of wind speeds measured at 10m above ground level nearby our location were acquired by works of (Ahmed, 2011; Colmenar-Santos, Campíez-Romero, Enríquez-Garcia, & Pérez-Molina, 2014; Mortensen et al., 2006). Since the rotor of our wind turbine stands in 30m AGL, the wind speeds had to be transposed to this height (Amar, Elamouri, & Dhifaoui, 2013) to be able to perform statistical analysis and finally calculate the annual energy output.

To do so, a Weibull distribution from which the cumulative distribution function could be derived was set up as below:

$$F(k, \lambda) = 1 - e^{-\left(\frac{v}{\lambda}\right)^{k}}$$

The parameter *k* is called the shape parameter, λ is the scale parameter, while v represents the wind speed. Through Matlab, the function parameters were computed and the following results were extracted:

k = 1.89 and **λ = 7.89 m/s**

The next step was to produce the wind exceedance curve which represents the number of days per year which the wind speed exceeds a specific value. By integrating the area between the days that correspond to the cut-in wind speed and those with respect to the cut-out wind speed (red area in the graph), the average annual energy output of our wind turbine and consequently its capacity factor can be calculated.

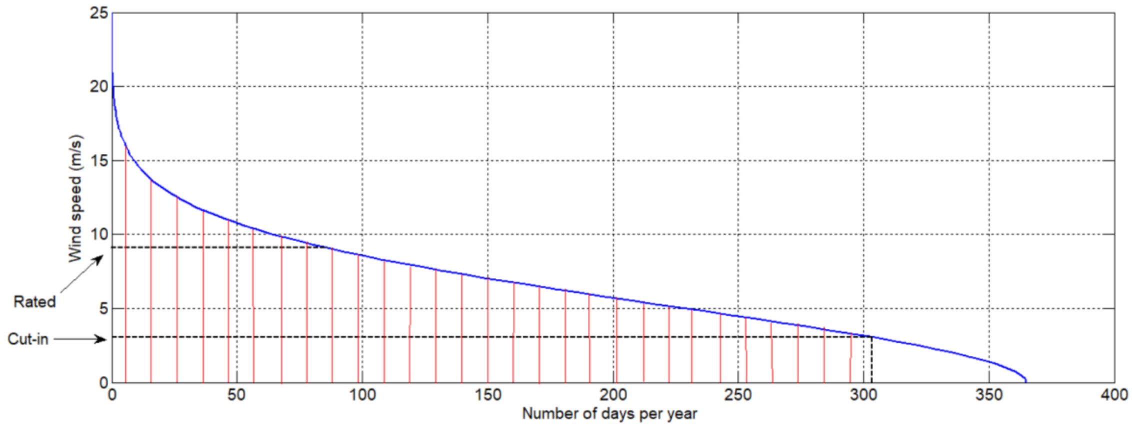


Figure 18 Wind exceedance curve

2.3.3. Selection of river current turbine

Given that the mean annual current speed in this part of the river reaches 0.8 m/s, as measured by Nile Research Institute, and due to lack of data regarding its variability throughout a year, multiple current turbines of relatively low rated power output were selected to use, instead of one with higher power capacity. The reason behind this decision lied on the power curve of the turbine; a current turbine which would have a nominal capacity of 20 kW would never actually generate more than 2 kW in this area because most of the time it would not operate under its rated speed, so it would not be economically viable.

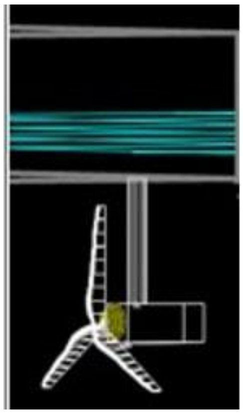


Figure 19 Current turbine design side view

Therefore, 4 current turbines of 5 kW nominal power capacity each were incorporated. The turbines are axial flow ones with a 5m rotor diameter, which is suitable for our case since the river current flow is unidirectional and thus, the cross-flow turbines would lose their advantage. The turbines are suspended underneath the platform base through a cylindrical shaft which is connected to their rotor and blades through their nacelle. The distance to each other was chosen to be 18m (more than 3 times their rotor diameter). This was done because, as Roberts et al. (2016) suggests, there has to be enough space in order to ensure that the turbulence created by the rotation of the front turbines' blades will have a minimal effect on the water flow and hence, the rear turbines' generation will remain unaffected. Moreover, a bottom clearance of 4 to 5 meters (depending on the water elevation levels) is considered, so that any impact on the riverbed sediments will be avoided.

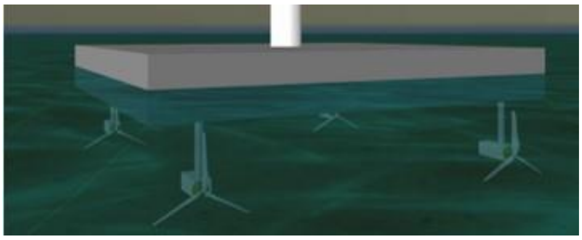


Figure 20 Current turbine design front view

The advantage in this idea is that these turbines could operate more effectively in lower stream velocities than a bigger one, plus they are considerably less costly.

2.3.4. Energy output

The average power output of each river current turbine is estimated through the following equation:

$$P_{ave} = \frac{1}{2} \rho_{water}\, c_p\, \pi R^2 v_w{}^3 = 1.76 \text{ kW}$$

Where **ρwater**= 1000 kg/m^3, **cp**= 0.35, **R**= 2.5m and **vw**= 0.8m/s

Consequently, the expected yearly energy output of each current turbine is calculated from the next formula:

$$E_{ave} = \frac{Pave \cdot 8760}{1000} = 15.41 \text{ MWh/year}$$

So, the total annual energy production from all the current turbines, as well as their capacity factor, is shown Table 2:

Table 2 *Annual energy production and capacity factor for the river current turbines*

Annual energy production	Capacity factor
61.64 MWh	35%

2.3.5.System energy output

Having calculated the energy generation from both the wind and the river current turbines, it can now be concluded that the system's energy production will be the sum of the two outputs, namely:

Total energy generation: 421.435 MWh/year

This number corresponds to the average annual energy consumption of approximately 130 typical households in Egypt, as the following graph dictates if a household consists of two residents on average is considered.

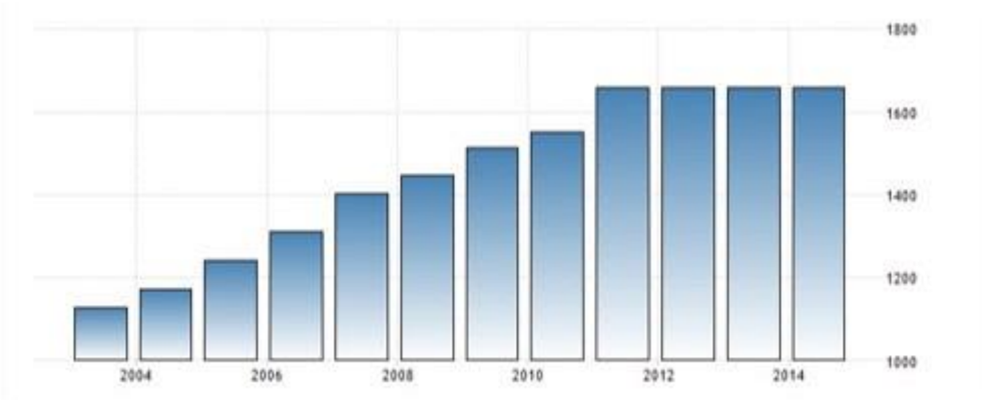


Figure 21 *Annual electric power consumption in Egypt (kWh per capita) (Tradingeconomics, 2018)*

2.4. Mooring Lines

2.4.1.Selection of mooring lines

The floating platform is tethered to the riverbed via mooring lines. The main role of the moorings is to maintain the system on station by not allowing extreme horizontal and vertical excursions and to be placed in a way that contact with other mooring lines of adjacent stations or with the electrical transmission cables will be avoided. A mooring system comprised of 4 catenary mooring lines was used. Each line is attached to one corner of the platform, while its other end is anchored on the river bottom through a drag-embedment anchor (Zanuttigh, Martinelli, & Castagnetti, 2012).

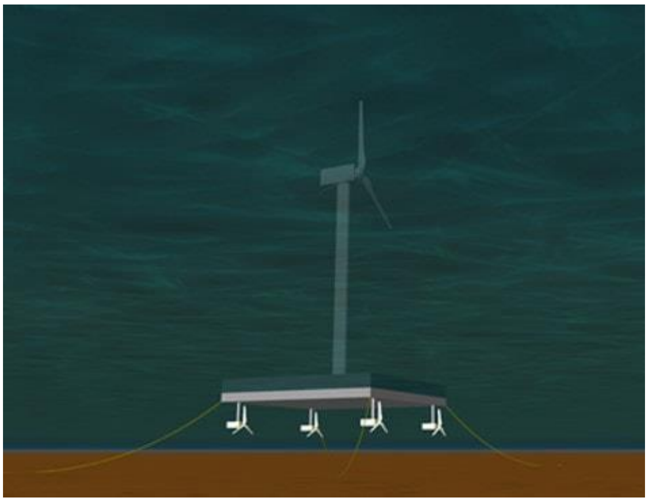


Figure 22 ***Mooring*** **lines** ***of HAPI*** **system**

The criteria on which were based to select the characteristics of the mooring lines are listed below:

1. A spread mooring system was chosen because it best obstructs the horizontal excursions of the platform and allows large compliance.
2. Catenary mooring lines were selected due to their suitability for shallow waters, which derives from their capability of providing their restoring forces through their suspended weight and from their subjectivity only to horizontal forces (Wang, Yang, Xu, & Liu, 2013). This is a significant difference in comparison to the taut lines, since the latter must be able to withstand vertical forces, as well.
3. The nominal diameter of each line was set to be **0.397m**. This was based on the platform weight, the water depth and the wave characteristics.
4. In order to ensure that the lines are able to withstand the exerted tensions on the platform without deformation or breaking, some of the important parameters which are shown on the following table were calculated. Following that, their durability was tested in the **Orcaflex** software.

Table 3 Mooring line parameters

Mooring Line Parameters	
Submerged weight per unit length $w=0.1875D^2$	29551.68 N/m
Axial stiffness per unit length $s=90000D^2$	14184810 kN/m
Proof load $P=21.6(44-0.08D)D^2$	149683.47 kN
Breaking load	23518.62 kN

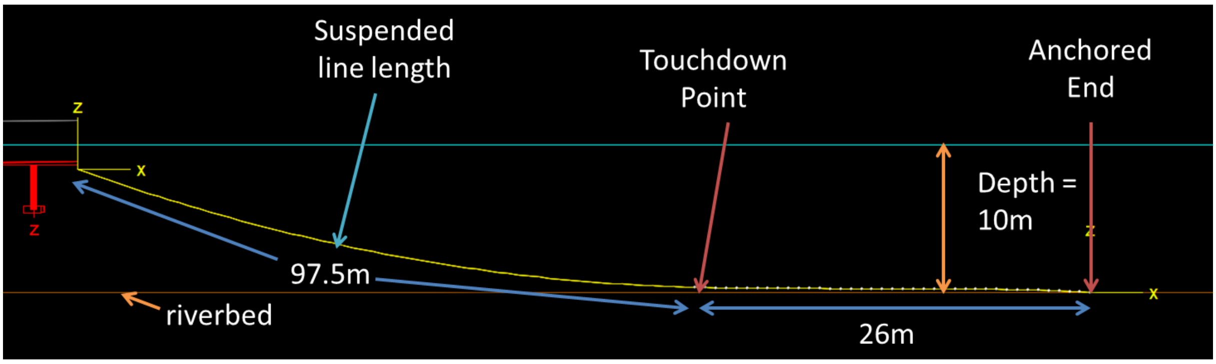


Figure 23 ***Mooring line design in Orcaflex software***

In the next table, the tensions of all mooring lines on their fairlead are calculated through Orcaflex. As can be noticed, all the line tensions are safely below their breaking load which means that the mooring lines can successfully hold the system in place.

Table 4 Line tensions under normal operation conditions obtained from Orcaflex

Dynamics complete

L35

Full results for Platform at time 6.600s

OrcaFlex 10.3a: HAPI mooring_v5 catenery.sim (modified 16:29 on 10/01/2019 by OrcaFlex 10.3a)

Dry length = 1.5844m.

Position (m)			Orientation (deg)		
X	Y	Z	Rotation 1	Rotation 2	Rotation 3
-0.0046	0.0000	0.0844	0.0002	-0.3695	0.0562

Connections							
	6D buoy end			Other end		Maximum tension segment	
Connection to	Total force (kN)	Vertical force (kN)	Total force declination (deg)	Total force (kN)	Uplift angle (deg)	Segment number	Tension (kN)
Ballast Tanks	2157.463	2157.463	180.0				
Current Turbine Tower 1	22.5968	20.7272	156.5289				
Current Turbine Tower 2	22.5968	20.7272	156.5289				
Current Turbine Tower 3	22.5968	20.7272	156.5289				
Current Turbine Tower 4	22.5968	20.7272	156.5289				
Line1 end A	2134.5188	527.1104	104.2969	2060.1238	0.0	A	2134.5151
Line2 end A	2134.5225	527.1093	104.2968	2060.1743	0.0	A	2134.5188
Line3 end A	2084.473	515.3348	104.3134	2001.5608	0.0	A	2084.4693
Line4 end A	2084.4729	515.3363	104.3134	2001.4928	0.0	A	2084.4691
Rotor and Blades	419.8307	-419.1441	3.2772				
Tower	199.9655	-199.9655	0.0				

2.5. Grid Connection

2.5.1. Introduction

After it has been ensured that the platform was stable under normal operation conditions, how it would be connected to the main grid should be examined. In this section, the components of the transmission line as well as the control system will be analysed. Figure 24 gives a better understanding of the concept, however, in our case the transformer is not necessary:

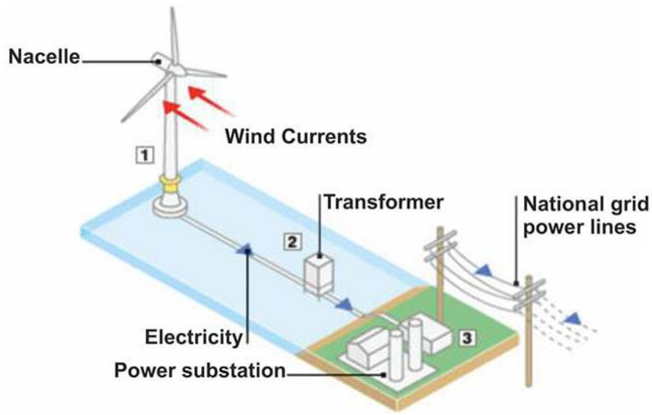


Figure 24 ***Grid connection concept of HAPI (Easywindenergy.blogspot.co.uk, 2018)***

2.5.2.Cables

The selection of the cables is a crucial factor in the connection with the grid. The platform and all the installed components on it are floating. Therefore, dynamic cables are required in order to keep the mechanical stresses induced on them within safe operating limits (Taninoki, Kazutoshi, SUKEGAWA, AZUMA, & NISHIKAWA, 2017). The critical point is the dynamic section of the cable because of the loads on the cables imparted by the motion in the turbine and mooring lines. The installation of these particular cables must be done by a specific cable laying vessel.

Figure 25 Dynamic cables (Industry, 2018)

Generally, the dynamic cables are characterized by excellent mechanical strength and they are not affected by twisting and bending moments. The Cross-linked Polyethylene (XLPE) insulation will protect the cables from the external damage which can be caused by other objects in the river (Qi & Boggs, 2006). Moreover, an intermediate buoy could be used in order to prevent the cables from being kinked near the riverbed.

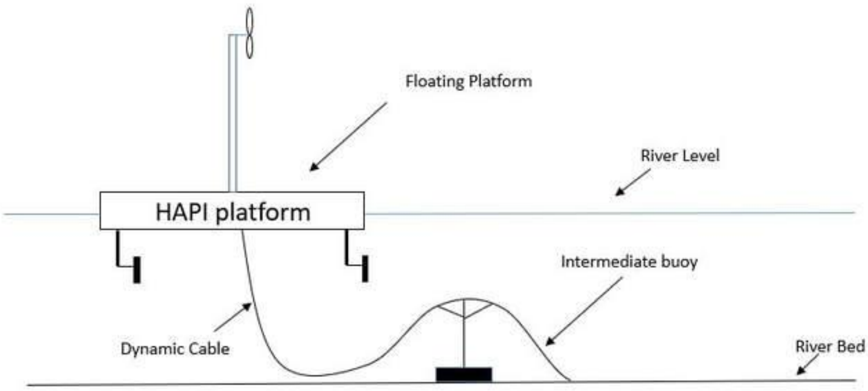


Figure 26 Dynamic cables representation in HAPI platform

2.5.3.AC or DC?

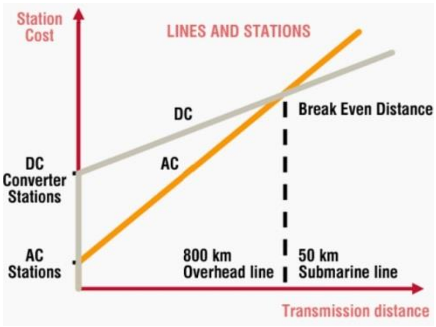


Figure 27 AC vs DC cost comparison (Edvard, 2014)

When it comes to the connection of an offshore system with the grid on the shore, usually there is a rival whether to use AC or DC cables (Green, Bowen, Fingersh, & Wan, 2007). Figure 27 shows that AC cost increases at a greater pace than the DC cost with distance. As it can be easily concluded our decision to use AC cables was straightforward. The nominal voltage of the cables is **400 V** which is identical to the voltage output from the wind and the water current turbines.

2.5.4.On-shore substation

The onshore substation is the linkage between our platform and the main grid. The main component of the substation is the 100 KVA frequency converter (Converter, 2018) which ensures that the frequency of the output signal is always within the accepted limits. Moreover, it provides the same functions as the typical onshore electrical substations: switching devices to connect or disconnect equipment, protection equipment to respond to faults, and transformation to higher voltages for either transmission to shore or feeding an AC/DC converter station.

Figure 28 The selected frequency converter

Generally, the power output of the offshore-wind turbine fluctuates during the day due to changes in wind speed. On the contrary, the power output from the water current turbines is not expected to change dramatically in a period of a day. However, even the small fluctuations affect the frequency and the voltage amplitude. For that reason, both turbine types are equipped with output voltage control system that keeps the voltage constant when the wind or water stream velocity changes.

2.5.5.Connection to the grid

The electric grid of Egypt is considered to be quite weak in our selected location and many regions nearby face often electricity blackouts due to the increasing demand (Mahdy & Bahaj, 2018). It is our responsibility to provide a steady voltage output that will not violate the flicker and harmonics limitations that are established by the Egyptian Electricity Authority. Our system will be connected to the local low-voltage substation as it is indicated in (Jeong, Kim, Moon, & Hwang, 2017). This will also enhance the distributed generation near this area and will gradually lead to a more stable electric grid.

3. ANALYSIS

3.1. Hydrostatics

3.1.1. Introduction

The main aim of this analysis is to check if the whole concept sustains the internal and external forces. The feasibility of the design depends on the behaviour of the structure in the water. The model that was simulated in **Maxsurf** software will be thoroughly described afterwards and it can be seen in Figure 29. The blades have not been designed due to software limitations but their weight has been included in the total weight of the turbines.

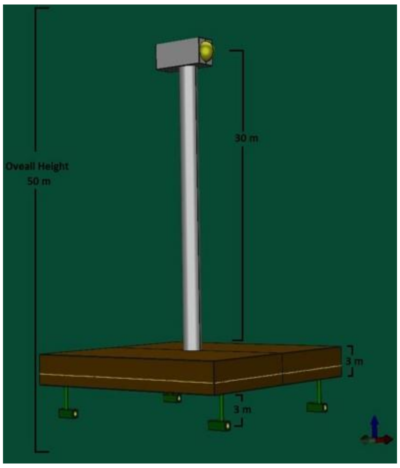


Figure 29 General Configuration

Table 5 System dimensions

Main Dimensions	
Platform Length	23m
Platform Breadth	23m
Platform Height	3m
Wind Turbine Blade Length	12m
Current Turbine Length	2.5m

More detailed information can be found in the Design Concept part.

3.1.2. Methodology

3.1.2.1. Theory behind the analysis

Every floating body experiences an upward force from the Archimedes' principle. This force is called **Buoyancy force**. It is equal to the weight of the fluid displaced by a fully or partially submerged body. It acts directly in the centre of the fluid displaced (Archimedes, 1897).

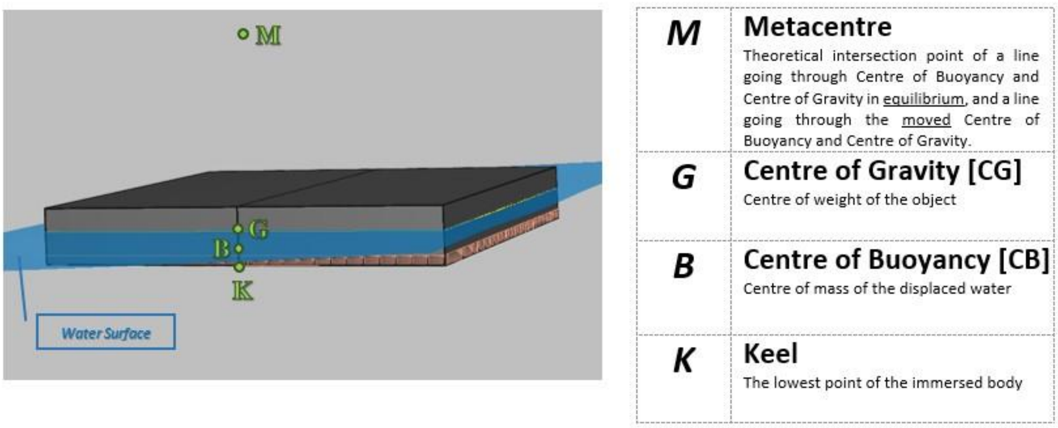


Figure 30 Hydrostatic Parameters

The most important rule for this concept is to have enough buoyancy force to carry all the weight groups by itself without sinking. In this sense, the stable equilibrium can be achieved when the total weight **[*Wind + 4x Current turbines + Platform*]** is equal to the buoyancy. If the weight exceeds the buoyancy, the object will sink. However, if the buoyancy exceeds the total weight of the body, the object tends to rise.

Every object tends to rotate under an external force application. This rotation changes the underwater shape of the immersed object. Consequently, the volume of the displaced fluid is changed and the position of the buoyancy centre along with it. This causes the **rotational moment.** For static stability of a floating body, it has to be able to return to its original position after a small change in the position of displacement caused by external forces – restoring force. This is a result of a centre of buoyancy change because the underwater shape of underwater body changes.

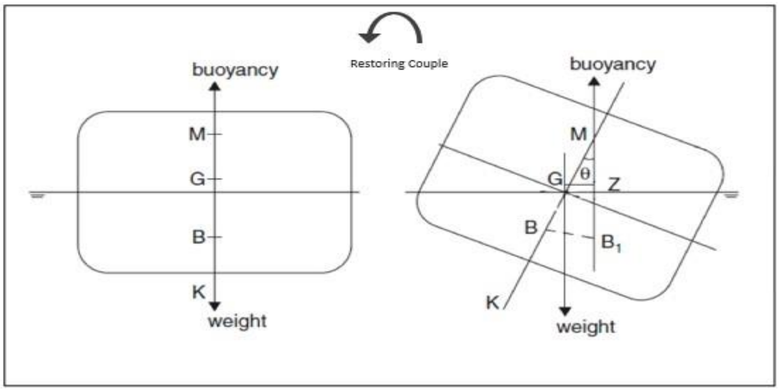


Figure 31 Stable Equilibrium (Biran & Pulido, 2013)

There are three conditions of the equilibrium based on the Metacentric height [GM] analysis (Tupper, 2013):

- Stable Equilibrium: The body returns to the original position

GM > 0 M is above G

- Unstable Equilibrium: The body continues to change its position and it can easily capsize

GM < 0 M is below G

- Neutral Equilibrium: The object keeps staying in the displaced position until a small change disturbs it and tends to return to the initial position or opposite – further away

GM = 0 M is coinciding with G

The main aim of the **hydrostatic** analysis is to find the balance of the component in order to achieve a stable equilibrium condition. This check was completed by computation of the equations below.

GM is called Metacentric height. Basically, it is a parameter which measures the initial stability of a floating object.

- ***KB*** is the vertical distance from the Keel to the CB

KB is found by half of the Draught (the vertical distance of the immersed body - how much is immersed

- ***BM*** is the vertical distance from the CB to the Metacentre

$$BM = \frac{I}{\nabla}$$	I -	Moment of Inertia
	∇ -	Volume of Displacement

Since the shape is very basic, the moment of inertia can be calculated from the following equation based on Length [L] and Breadth [B] of the platform:

$$I = \frac{LB^3}{12}$$

- ***KG*** *is the vertical distance from the Keel to the CG – equal to the barge height*

3.1.3. Analysis and Results

In order to achieve successfully working product, the HAPI concept has been designed and analysed in **Maxsurf** software which are described below. Moreover, the stability analysis has been performed and the results were compared to the existing classification body regulations – DNV GL and IMO (DNV GL, 2014). In this project, Maxsurf Modeler and Maxsurf Stability were used.

3.1.3.1. Maxsurf analysis

The pictures below show the look of the HAPI concept designed in Maxsurf Modeler. The DWL means Draught Waterline. The *Designed draught* of the platform is *1.19m* but after addition of ballast tanks for better stability, the *Draft Amidships is 1.6m*.

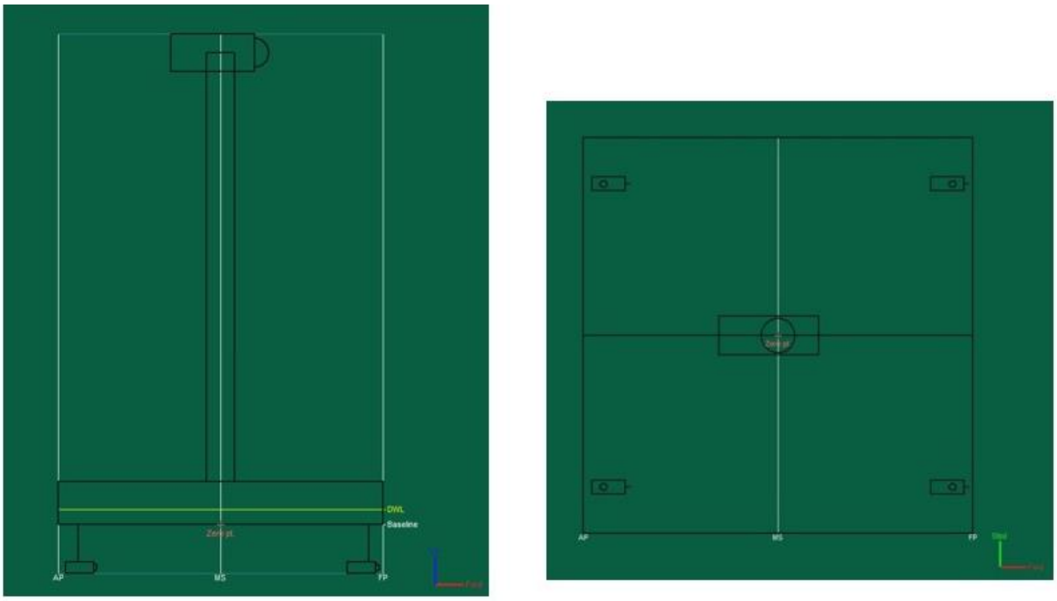
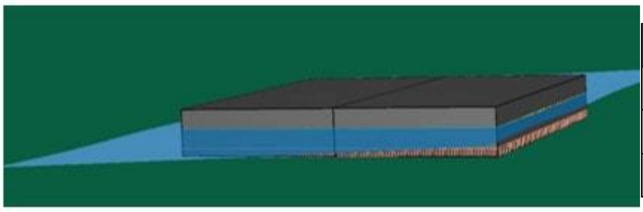


Figure 32 Side and top view in Maxsurf

An addition of ballast tanks had to be applied in order to achieve better stability of the structure. The tanks are filled up with Concrete with the density of 2.08 t/m^3.



Ballast Tank Information	
Length	5 m
Breadth	11.5 m
Height	0.2 m

Figure 33 Ballast Tanks View and information

3.1.3.2. Dead load

All the weights of the structural components are listed in Table 6 in order to calculate its stability. The Wind and Current turbines weights include full electrical and mechanical equipment provided by the supplier. Moreover, the Platform weight includes the weight of Stiffeners and Girders.

Table 6 Components' weights

Component	Weight (tonnes)
Wind Turbine	29.65
Current Turbines (4 x 2.5t)	10
Platform	610
Ballast	220.05
Total	869.7

3.1.3.3. Hydrostatic results

The results from the stability analysis are combined in a table below.

Note: All the measurements are according to the coordinate system with the following origin:

X = 0 at MS (Midship), positive forward

Y = 0 at centre line, positive to starboard side (sometimes marked with “S” or “P”).

Z = 0 at baseline of the platform, positive upward.

Table 7 Hydrostatic Results

Hydrostatic Results	
Draft Amidships m	1.6
Displacement t	869.7
Heel deg	0
Draft at FP m	1.6
Draft at AP m	1.6
Draft at LCF m	1.6
Trim (+ve by stern) m	0
WL Length m	23
Beam max extents on WL m	23
Wetted Area m^2	704.478
Waterpl. Area m^2	529
Prismatic coeff. (C_p)	0.959
Block coeff. (C_b)	0.33
Max Sect. area coeff. (C_m)	0.344
Waterpl. area coeff. (C_{wp})	1
LCB from zero pt. (+ve fwd) m	0.011
LCF from zero pt. (+ve fwd) m	0
KB m	0.792
KG fluid m	1.906
BMt m	27.484
BML m	27.484
GMt corrected m	26.37
GML m	26.37
KMt m	28.276
KML m	28.276
Immersion (TPc) tonne/cm	5.422

MTc tonne.m	0
RM at 1deg = GMt.Disp.sin(1) tonne.m	400.253
Max deck inclination deg	0.0184
Trim angle (+ve by stern) deg	0

3.1.3.4. Large angle of stability

The Static Stability Curve (GZ curve) is one of the most important tools for measuring the stability of a floating object. There are several features to be outlined (Biran & Pulido, 2013):

- The largest steady heeling moment the platform can withstand without capsizing
- Vanishing angle – when the GZ becomes zero, is the largest angle that the platform can return after the loading is removed
- Important for freeboard and reserves of buoyancy

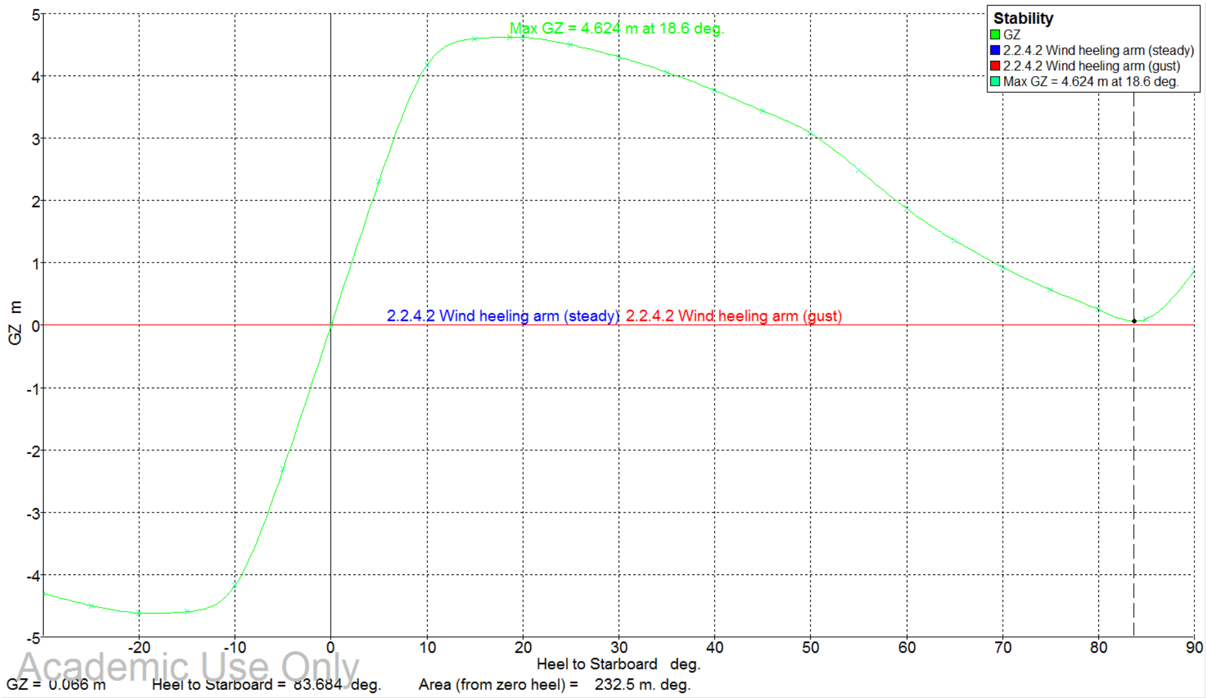


Figure 34 The Static Stability Curve of Hapi platform

3.1.3.5. Rules and Regulations

HAPI concept has been crossed checked with the existing regulations for similar floating concepts. There are two regulating bodies which are responsible for checking this type of structures – DNV GL (Det Norske Veritas and Germanischer Lloyd) and IMO (International Maritime Organisation). The regulations for floating pontoons/ barge are met during the stability calculations (DNV GL, 2017).

Table 8 Stability Guidelines Check

DNV GL Guideline Check for barges / pontoons						
2.2 Pontoons	2.2.4.2 Wind heeling arm					
	Wind arm: a P A (h - H) / (g disp.) cos^n(phi)					
	constant: a =	0.99997				
	wind pressure: P =	504	Pa			

	area centroid height (from zero point): h =	0	m			
	total area: A =	0	m^2			
	H = mean draft / 2	0.8	m			
	cosine power: n =	0				
	gust ratio	1.5				
	Intermediate values					
	Heel arm amplitude		m	0		
2.2 Pontoons	2.2.4.1 GZ area: to Max GZ				**Pass**	
	from the greater of					
	angle of equilibrium	0	deg	0		
	to the lesser of					
	angle of max. GZ	18.6	deg	18.6		
	shall be greater than (>)	4.5837	m.deg	61.612	**Pass**	1244.16
2.2 Pontoons	2.2.4.2 Angle of equilibrium ratio				**Pass**	
	2.2.4.2 Wind heeling arm					
	Ratio of equilibrium angle to	Deck Edge Immersion Angle				
	shall be less than (<)	50	%	0	**Pass**	100
	Intermediate values					
	Equilibrium angle		deg	0		
	Deck edge immersion angle		deg	6.9		
2.2 Pontoons	2.2.4.3 Angle of vanishing stability <=100m in length				**Pass**	
	shall be greater than (>)	20	deg	90	**Pass**	350
2.2 Pontoons	2.2.4.3 Angle of vanishing stability >=150m in length				**Pass**	
	shall be greater than (>)	15	deg	90	**Pass**	500

3.1.4. Conclusions

From the calculations above, it can be seen that the HAPI concept satisfies all of the regulation criteria. The floating concept for producing clean electricity from wind and current turbines shows that the equilibrium of the floating body has positive stability. Also, the initial metacentric height guarantees for large initial stability.

The results were compared mainly with pontoon shape and general criteria applicable for all ships in order to produce maximum close to the real result. The criteria provided by the software are limited in this case. Further analysis and consultation are needed with the consultation organisations and classifications bodies before releasing the project.

3.2. Loading

3.2.1.Load Analysis

The loads which our system is subject to are of different kinds. The understanding of the way that these loadings operate on the wind and the river current turbines are of paramount importance to avoid their catastrophic failure (Xu & Ishihara, 2014). Therefore, the most basic types of loads need to be described, whereas the ones with the highest impact on our structure are thoroughly explained and calculated. The aim of this procedure was to ensure that our system can withstand the external forces acting on it without deformation or significant displacement of its equilibrium position and that its dynamic responses to the imposing loads are within the permissible limits, resulting in its safe operation.

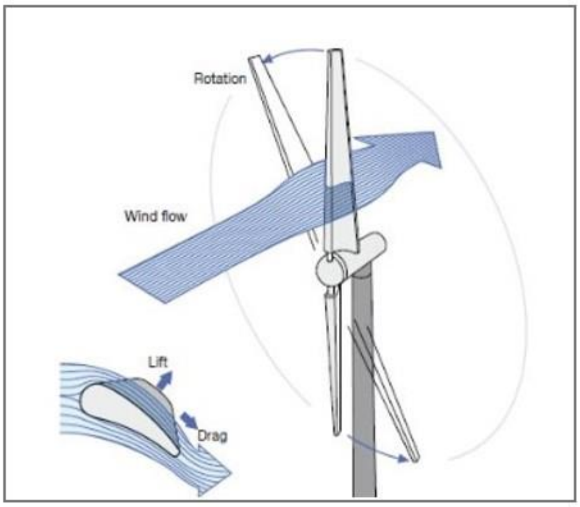


Figure 35 Aerodynamic force on a wind turbine (Cleanenergybrands, 2018)

The major elements of loading on our system are the hydrodynamic loads (wave loads and current loads) on the platform and on the current turbines, the aerodynamic loads on the wind turbine's rotor, the gravitational loads from the wind turbine, the platform and the current turbines, as well as the buoyancy force produced by the volume of displacement of the system in the water (Liu, Lu, Li, Godbole, & Chen, 2017). There are, however, more loads that are applied to the components of the structure, such as functional loads from transient operation conditions (braking torque, yawing moment, blade pitching moment) or inertia loads from vibration or gyroscopic effects, but it was not in the scope of this study to involve in these areas (Gwon, 2011).

In this work, it was decided to neglect the hydrodynamic load from the wave motion, since in this area, the waves are usually very small in height and long in period. Consequently, the main interest was set in the aerodynamic load created by the axial thrust force of the wind on the rotor of the wind turbine and the corresponding horizontal force on the current turbines induced by the water stream which are both calculated below for normal operation conditions, as presented in Figure 36.

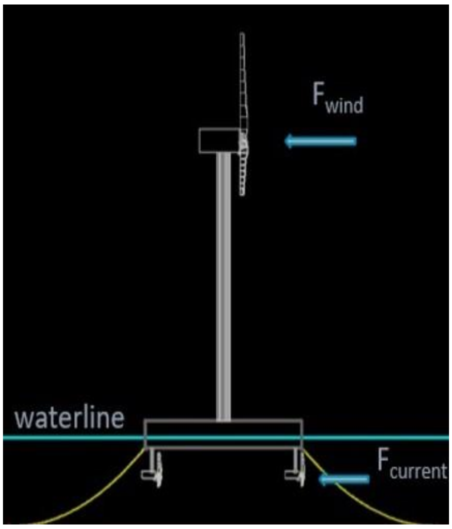


Figure 36 Wind and river current forces acting on the hybrid system

The thrust force of the wind is given through the following equation:

$$F_{wind} = \frac{1}{2} C_T \rho_{wind} A_{wt} V_{wind}^2 = 24 \text{ kN}$$

where F_{wind} is the wind thrust force, C_T is the thrust coefficient (which is set to be 2 for normal operation), ρ_{wind} = 1.225 kg/m^3 is the air density, $A_{wt} = \pi R^2$ is the swept area of the wind turbine blades and V_{wind} is the wind speed. Considering that the average annual wind speed at hub height on our site is 6.6 m/s^2 and the wind turbine blades' radius is 12m, the above results are calculated.

Similarly, the horizontal force of the water current on each current turbine is given through the same equation, in which ρ_{wind} is replaced with ρ_{water}= 1000 kg/m^3 for fresh water, $A_{ct} = \pi R^2$ with the radius of each turbine's blades to be 2.5m, the thrust coefficient is set to be 1.5 for the water and $V_{current}$ = 0.8 m/s is the average annual water current velocity in this part of the Nile.

Therefore **Fcurrent = 9 kN**

As it can be noticed, the directions of these forces are antiparallel with respect to the waterline axis. That means that the bending moments they cause in the system are counterbalancing and hence the system achieves dynamic stability. It is safe to assume that this is the usual case since the wind direction in the chosen location shows that the direction of the wind is mostly stable throughout a year (Easywindenergy.blogspot.co.uk, 2018).

However, it needs to be proved that the system's dynamic response will not be seriously affected regardless of the wind direction. The dynamic analysis conducted in Orcaflex software led to the following results in terms of platform's rotating motions:

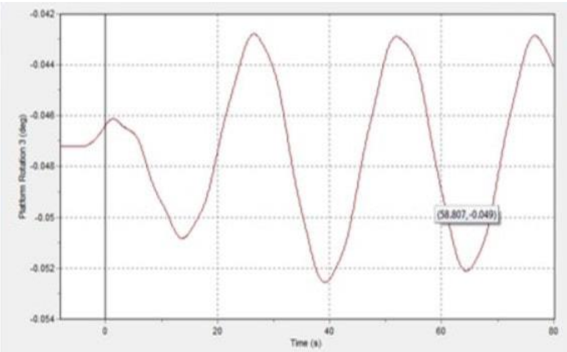


Figure 37 Platform roll rotation

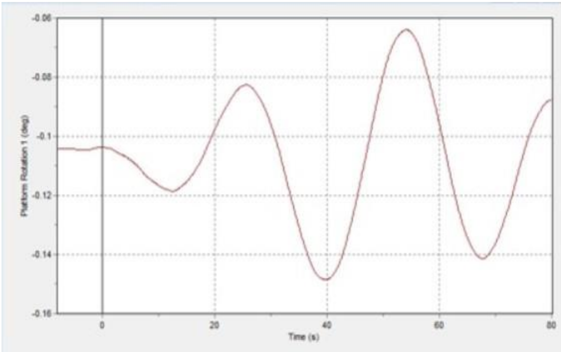


Figure 38 Platform yaw rotation

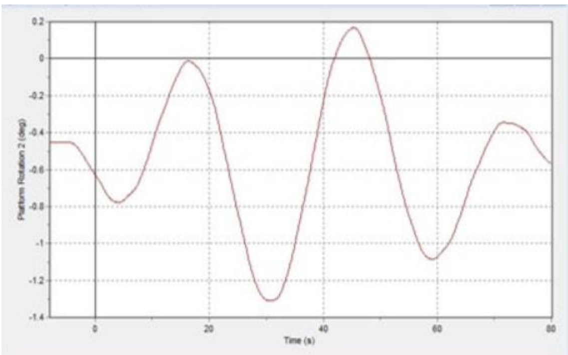


Figure 39 Platform pitch rotation

As it can be directly extracted from the above diagrams, the platform's rotation is minimal in roll and yaw directions, while in pitch direction it stays at very low levels as well. The result is that in normal operating conditions, the system can safely respond to the acting external forces without compromising its dynamic stability.

3.3. Financial Analysis

3.3.1.Introduction

After the technical analysis has been done, the financial analysis was carried out. This was done in order to break down the project cost and to determine the amount of money the consumers need to pay for electricity. Since our aim is to investigate the feasibility of the project, it also needs to be economically beneficial. In this section, the financial analysis was concentrated on three main tasks:

- **Levelized Cost of Energy**
- **Payback Period**
- **Sensitivity Analysis**

3.3.2.What is LCOE?

Levelized Cost of Energy (LCOE) is the minimum cost to generate electricity, also known as the estimated energy production cost, in which the energy must be sold to make the project profitable. In order to calculate LCOE, the initial capital, operation and maintenance costs and other costs of transmission lines and substation for any power generation need to be considered. The LCOE can be expressed in £/MWh or p/kWh. The equation used to calculate the LCOE (Keeley, 2016) has been expressed as follows:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t + M_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{Q_t}{(1+r)^t}}$$

where:

- **Ct**= Total Initial Capital or Investment expenditure of the project in year t
- **Mt**= Operation and maintenance expenditure in year t
- **Qt**= Annual Energy Generation in year t
- **r**= Discount rate
- **T**= Life cycle of the project

3.3.3.Initial Capital Cost (CAPEX) and Operation & Maintenance Cost (OPEX)

Since the nominal wind power output is 100kW, the capital cost of the wind turbine has been taken from the statistics based on the current price of the commercial small scale wind turbines (N. M. Eshra, Abdelnaby, M. E, 2014). The annual OPEX was considered in two categories (N. M. Eshra, Abdelnaby, M. E, 2014; Hou, Enevoldsen, Hu, Chen, & Chen, 2017) which is 1.5% of CAPEX for the first half of life cycle and 2% of those for the latter half of the period. The capital and O&M cost of the wind turbine can be seen in Table 9. As the horizontal type current turbine has not widely commercialized at the moment, the CAPEX and OPEX of current turbines have been made as an assumption from the prices mentioned in the article, (N. M. Eshra, Abdelnaby, M. E, 2014). The description of the current turbines costs can be found in Table 9 as well.

Table 9 CAPEX and OPEX of wind and current turbines

100kW Wind urbine	
Capital Cost	£37,440
Operation and Maintenance Cost	£579.60
4x5kW Current Turbines	

Capital Cost	£20,400
Operation and Maintenance Cost	£510

The capital cost of the platform has been calculated by using analytical weight cost relation method considering the index of 2018 EU and World Steel price (Statista, 2018). The capital cost of the platform was estimated to be £14,000 including the building cost and the substation cost was assumed to be £8,500 covering with the costs of transmission and mooring lines.

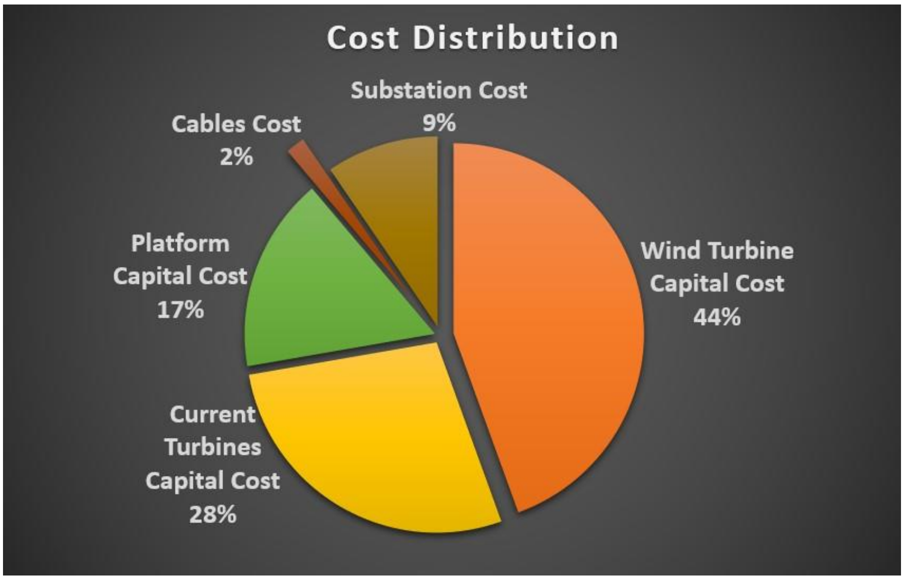


Figure 40 Cost Distribution Chart of the system

At this point, the project was considered to have 20 years of a lifetime which is the typical life cycle for wind turbines. Then the LCOE was calculated and the result is shown below:

LCOE = 0.142 p/kWh

3.3.4. Payback period

The payback period of the project was estimated as well. The detailed calculation procedures can be found in the Financial Analysis Excel spreadsheet and the result of the calculation can be seen in Figure 41. If the annual electricity is produced properly, we expect that a profit could be made within 11 years of project life.

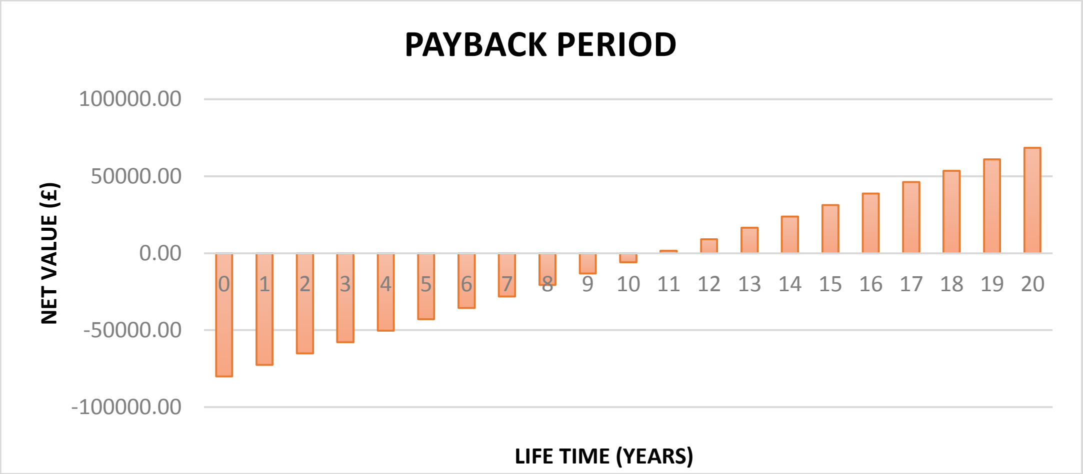


Figure 41 Payback period of the system

3.3.5. Sensitivity analysis

The sensitivity analysis for LCOE was investigated for the project. The calculation was assumed by changing the capacity factor of both wind and current turbines. Since the project is proposed to be deployed in the river, in some point the energy could not be produced properly in the downtime weather condition affecting power generation. This may result in the rise of LCOE. The results have been summarized as follows:

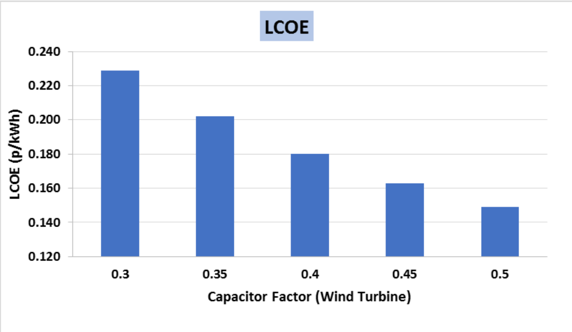


Figure 42 LCOE with Capacitor Factor Changes (Wind Turbine)

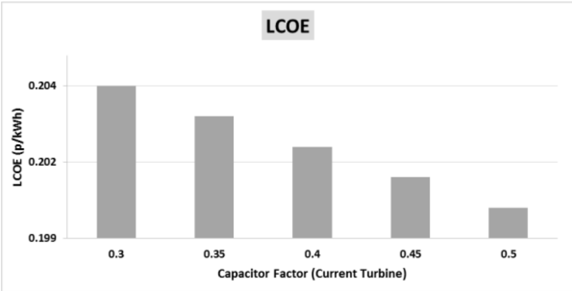


Figure 43 LCOE with Capacitor Factor Changes (Current Turbine)

The following Figure 44 gives a better understanding of how the capacitor factor affects the power output of the turbines:

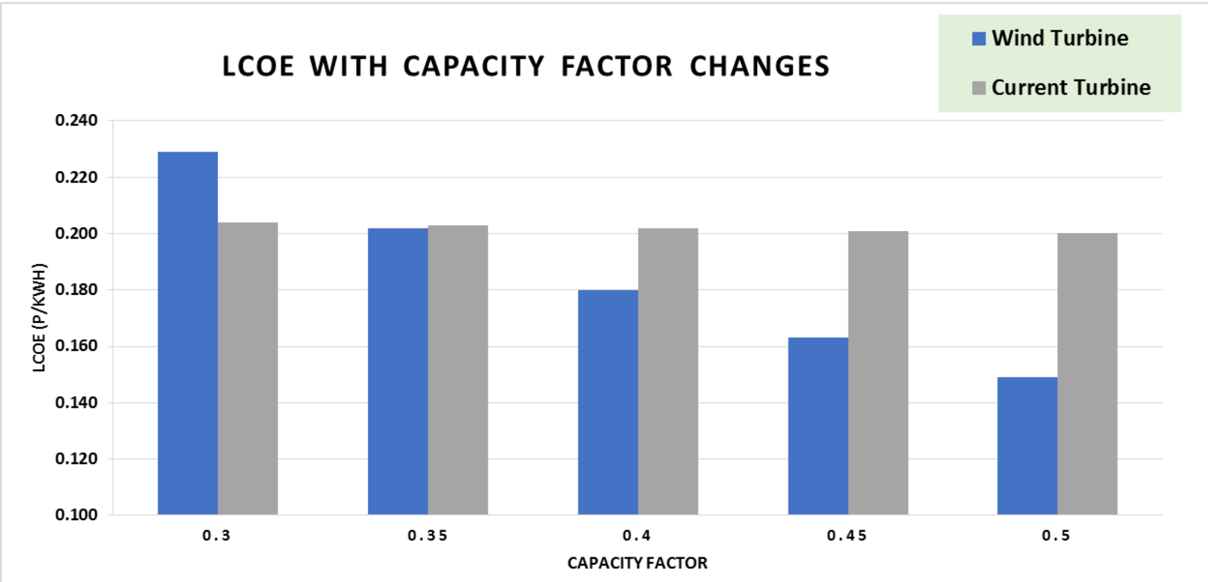


Figure 44 Comparison of LCOE with Capacitor Factor Changes

3.3.6. Conclusions

The conclusions can be summarized into two different views based on the estimated results and future expectation. First of all, the LCOE of 14 p/kWh is moderate for the energy production, therefore it is expected the strike price is to be **16 p/kWh**. In order to make an effectively profitable project, the strike price should be higher than the LCOE. But the expected value is slightly expensive for the local Egyptian households (Yousri, 2011). Therefore, another option was investigated to reduce the cost. Since the Egyptian Government targeted that by 2010 20% of National Energy Production will come from the Renewable Energy Sector (Enterprise, 2018; Export.gov, 2018), it is safe to believe that the government subsidies would be available in order to reduce the project cost. Lastly, a sensitivity analysis was carried out only for the capacity factor changes which was considered as the major influence parameter. However, there are other parameters which affect LCOE, such as, the running costs but it was not in the scope of this work to investigate how they could be reduced. Consequently, they were considered stable over the years. After all, it is concluded that with the appropriate governmental support our project would be economically viable with a normal payback period.

3.4. Environmental Analysis

3.4.1. Introduction

Nile's length across Egypt is more than 1000 km hence it has played a major role in the development of the Egyptian civilization in history. The Nile is the main resource of food and water for the local people and more than 90% of fresh water supplies are coming from it. Moreover, it makes Egypt one of the largest freshwater fish producers around the world due to its excessive fish farming activities along the river (Soliman & Yacout, 2016). It has been estimated that thousands tons of freshwater fishes are farmed annually. The figure below gives us a clear view of the annual aquaculture production (in tons per year) of the year 2012.

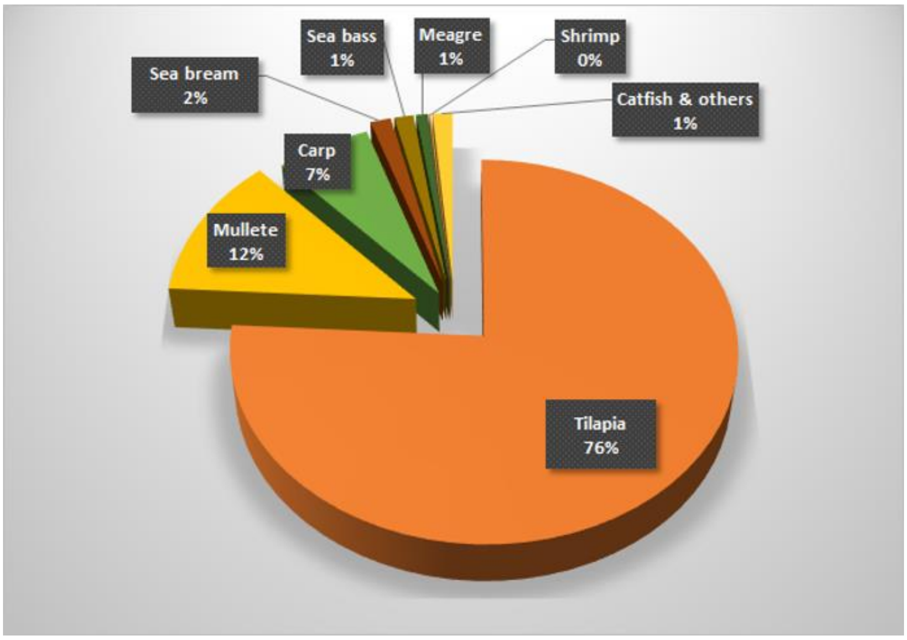


Figure 45 Features of aquaculture production (Shaalan, El-Mahdy, Saleh, & El-Matbouli, 2018)

The Nile authorities are quite sensitive regarding the environmental laws and legislations. The Ministry of Environment, other governmental agencies and local authorities play an important role and are responsible for setting the environmental rules and regulations. According to the Ministry of State for Environmental Affairs (Ministry of Environment Egyptian Environmental Affairs Agency, 2018), the current legislative requirement for any proposed project in the Nile must be considered under the LAW NUMBER 4 OF 1994, PROMULGATING THE ENVIRONMENT LAW (amended Law No.9 for 2009). It mentions that the environmental data and impacts such as land use, surface water, air quality, biodiversity, bird and fish species, noise and vibration need to be taken into account for any power generation development.

3.4.2.Potential impact

Since the project is proposed in the Nile, the potential impacts which may occur during the construction and lifetime operation of the project have been considered (El Gohary & Armanious, 2017). Some of the major and minor impacts have been summarized as follows:

Figure 46 Tilapia, the most common fish in Nile

- Impacts on land use and local infrastructure
- Impacts of air, noise and water quality on near areas and villages during the construction
- Impacts on hydrology and downstream flows
- Potential impacts on fish farming changes
- Impacts on fish swimming behaviour and migration routes

The areas of land use for the substation and the transmission lines are not significantly wide to be considered as a major impact. Subsequently, the project might not essentially affect the hydrology and water quality of the river. Therefore, the main effects of those impacts have been considered as minor. However, the changes in the fish farming area are meaningful concerns for the environmental footprint.

The operation and vibration of the wind and current turbines may affect the features traits of the fish swimming behaviour (Shaalan et al., 2018). Fish movement might be restricted as well since there is no significant space below the platform. Therefore, there might be subsequent effects related to the habitat connectivity and the migration routes.

3.4.3.Possible mitigation

In the following table, a summary of different proposed mitigation strategies is outlined, as an effort to minimise the negative environmental consequences described above.

Table 10 Impact mitigation matrix proposed for HAPI project

Potential Impact	Impact duration	Magnitude of Impact	Mitigation methods
Noise and Vibration	Construction and Operation	Moderate negative impact	• Using noise minimization program • Develop site management and reduce speed limits
Land use and Visual impact	Entire project life	-Minor impact -Small scaled project	None required
Air and Water Quality	Entire project life	-Minor impact -Almost zero Carbon Small scaled project	None required
Fish farming and Migration changes	Entire Project life	Major impact	• Adopting the best practice on the width of gaps for the fish to pass through the site areas • Using fish friendly turbine and modification for large array farm • Investigation on Rotor Avoidance Zone

3.4.4.Conclusions

The investigation of the impacts and possible mitigation procedures showed that the project implementation is deemed to be secure for the fish farming and the hydrological changes of the river. Nevertheless, a thorough investigation of the visual impact on landscape needs to be performed for the possibility of a large array farm. In a nutshell, the project seems to present a good level of environmental friendliness under the designated conditions.

4. Concluding remarks

4.1. Key outcomes

The investigation of HAPI concept led to various interesting conclusions in terms of both its technical aspects and its social footprint. Having selected an appropriate location with favourable features to deploy our system, we then focused our efforts on exploring its ability to perform effectively under ordinary circumstances. As a result of this research, the main outcomes are:

- The feasibility of our design was ensured since its stability under normal operating conditions was tested and achieved.
- The energy generation from our system is expected to cover the local electricity needs at a sufficient level.
- This innovative idea could attract governmental subsidies and thereby, as our financial analysis confirmed, it would be rendered cost-effective and worth constructing.
- Its minor impact on the surrounding areas and on river life makes it a sustainable project, which would have multiple benefits for the local communities.

Figure 47 HAPI system

4.2. Recommendations for future work

Due to physical limitations concerning the scope and the timeframe of our project, we could not delve deeper into every aspect of the concept, as we would have liked to. Therefore, there are some issues that need to be further investigated in future time, so that we have a complete picture of the potential of this idea.

Initially, a complete structural analysis should be made, so that the system response will be tested under extreme environmental conditions. Also, despite that we tried to achieve a considerable total power output to meet the local demand as much as possible, the site conditions would not allow us to install a higher power capacity system, because the river waters are too shallow to accommodate a larger floating structure. Nevertheless, a potential enhancement in energy generation could become possible by building arrays of hybrid systems alongside the river. Finally, the development of a suitable storage system which could be installed onshore and directly connected to our system is considered as a necessary prospect, because it would ensure the dispatchability of the system energy production and hence, its disengagement from the unpredictability that stems from the stochastic nature of the wind.

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http://www.esru.strath.ac.uk/EandE/Web_sites/17-18/hapi/

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